# Carbon Dioxide Removal Mission

## Life Cycle Analysis and Techno-Economic Analysis Technical Track Action Plan

## 2023-2028

# Table of Contents

## Introduction to the Carbon Dioxide Removal Mission

Carbon removal has been identified as an essential tool in the suite of climate actions. Alongside dramatic emissions cuts, the global community will need solutions to remove billions of tons of $CO_2$ from the atmosphere every year to limit the impact of climate change (IPCC 2022 - SPM)[1].

The Carbon Dioxide Removal Mission under Mission Innovation (MI CDR) aims to enable CDR technologies to achieve a net reduction of 100 million tonnes (0.1 gigatons) of $CO_2$ per year by 2030.

The Mission endeavors to achieve its goal through activities informed by innovation priorities, and organized around three short-term outcomes:

- **Outcome 1: Enhanced understanding of local and global CDR potential**
- **Outcome 2: Advancement of R&D for CDR technologies**
- **Outcome 3: Global demonstrations and pilot-scale tests**

The Mission currently prioritizes three key engineered and hybrid CDR approaches[2]: direct air capture (DAC) with storage; biomass with carbon removal and storage (BiCRS); and enhanced mineralization (EM). The Mission is not currently exploring ocean-based or entirely nature-based CDR strategies such as afforestation, improved forest management, or wetland restoration[3].

The CDR Mission is co-led by the USA (***Department of Energy-DOE***), Canada (***Natural Resources Canada-NRCan***), and the Kingdom of Saudi Arabia (***Ministry of Energy***). Members include Australia (***Commonwealth Scientific and Industrial Research Organization-CSIRO***), the European Commission, India (***Ministry of Science and Technology***), Japan (***National Institute of Advanced Industrial Science and Technology (AIST)***), Norway (***Gassnova***), and the United Kingdom (***Department for Business, Energy, and Industrial Strategy***).

## Introduction to the LCA/TEA Technical Track

The mass deployment of CDR technologies and approaches will require an advanced understanding of the complex social, economic, and environmental challenges and opportunities associated with each approach.

Life Cycle Analysis (LCA) and Techno-economic Assessment (TEA) are key science-based decision-making tools that can address these questions.

LCA is the most widely used methodology to assess products, processes, and systems on their entire life-cycle environmental performance. This is critical in the case of CDR, where all upstream and downstream GHG emissions must be quantified and included in the emission balance of a specific technology, with the total removal of GHG emissions being larger than the total emissions. Further, LCA is a flexible methodology that can be used to quantify a wide variety of environmental and social impacts. The quantified LCA data are useful for optimizing

[1] IPCC Summary for Policy Makers.
[2] Hybrid approaches use technology to supplement natural $CO_2$ removal processes. Biomass with Carbon Removal and Storage (BiCRS) and enhanced mineralization are examples of hybrid approaches.
[3] Subject to members' interest and capacity, the CDR Mission could explore other CDR approaches. The LCA/TEA technical track may reconsider the scope of activities accordingly and/or subject to member capacity.

the design and operation of CDR technologies to mitigate their impacts and improve effectiveness in increasing $CO_2$ removal.

TEA is a decision-making tool used to evaluate technology options based on technical, economic, environmental, social, and regulatory criteria. Although TEA-related activities have not been clearly delineated in this Action Plan, they are either part of the currently identified activities or can be further developed in the future, as TEA shares similar technical challenges as well as innovation gaps with LCA. Together, LCA and TEA allow decision-makers to account for the key technical, environmental, economic, social, regulatory, and political factors that influence the rate at which CDR solutions will be deployed at a local, national, and international scale. As such, the LCA/TEA Technical Track is a cross-cutting theme for MI CDR, underpinning each of the approaches to carbon dioxide removal.

## Purpose of the LCA/TEA Technical Track Action Plan

The purpose of this document is to outline the proposed work of the LCA/TEA technical track including to:

- Define an agreed scope of work through inputs and feedback from all participants.
- Roadmap the potential actions of the LCA/TEA technical track.
- Initiate and identify specific LCA/TEA case studies.
- Engage with key CDR stakeholders and attract potential new member countries to the track and advise where their expertise will be useful.

This is a living document and as the CDR space is continuously and rapidly evolving the co-leads encourage inputs, changes, and updates of any kind.

## LCA/TEA Technical Track: Commitments, Roles, and Responsibilities

All Member countries of the track will:

- Actively participate in knowledge exchange with other members.
- Perform tasks and studies, and supply information/data as agreed.
- Contribute to data sharing hub to address data gaps.
- Provide input and comments as requested to plans and reports within an agreed time.
- Be part of the organization and execution of workshops and seminars/webinars.
- Suggest and contribute to common calls and commit to funding as agreed.
- Involve the research community, private industry, academia, and other relevant stakeholders in agreed countries to participate in the Mission activities within LCA/TEA technical track.

## Objectives of the LCA/TEA Technical Track

A central goal of the LCA/TEA track is to contribute to efforts to ensure that scaled-up CDR solutions and their value chains can enable global net-zero goals, without significant harm to other key social and sustainability goals such as those defined by the UN Sustainable Development Goals[4]. The evidence will be important to give societal and market confidence to CDR, e.g., to enabling markets for credits for carbon removals.

An enhanced understanding of the impacts over the lifecycle of CDR technologies will boost societal and market confidence and ensure increased and continuous investments that will help take these emerging technologies to maturity and commercial viability. Harmonized LCAs and TEAs will enable more accurate assessments of all carbon dioxide removal technologies. To develop an *Enhanced Understanding of Local and Global CDR Potential* (Carbon Dioxide Removal Mission: Action Plan, Section 2.0), the LCA/TEA Technical Track will work to:

- **Objective 1: Advance Globally Shared Best Practices**
    - Increase transparency and/or work to harmonize LCA and TEA approaches and methodologies through collaboratively developed guidelines and best practices.
- **Objective 2: Assess and Address Data Gaps and Data Access**
    - Improve the quality of data to support LCA across each of the DAC, BiCRS, and EM approaches to carbon dioxide removal.
- **Objective 3: Identify and Launch a Global Data Sharing Hub**
    - Advance global capacity to undertake rigorous LCAs through the development of open-source tools and models for LCA/TEA for CDR technologies, and the creation of publicly available data sets.
- **Objective 4: Assess CDR Scale-Up**
    - Expand the boundaries of LCA/TEA to consider the environmental and economic impacts of CDR deployment at scale, considering the impacts of increased competition for resources such as feedstocks, land & water.

Projects under the LCA/TEA technical track will focus on defining system boundaries for specific technologies and regions, improving data availability for modeling efforts, standardizing methodologies, enhancing understanding of CDR scale-up, and developing comparable functional units to easily compare results across different CDR technologies and regions.

Activities to be undertaken to advance each of these objectives are described below.

### Participants

Member countries, namely Canada (co-lead), Japan (co-lead), and the United States will support this project. Norway will lead BiCRS LCA case studies, and Saudi Arabia and Australia will support LCA case studies for enhanced mineralization. Japan will lead the DAC LCA case studies. To deliver the project, leads will collaborate with academic organizations, as well as

[4] UN Sustainability Development Goals

federal and governmental research organizations. Collaboration with industry, who have expertise and experience with LCAs, will also be an important component of the work.

## LCA/TEA Track Objective 1: Advance Globally Shared Best Practices

Existing assessments of the environmental and economic performance of CDR technologies have relied upon different methodologies and assumptions, leading to wide discrepancies in results within single technological pathways. The lack of consistent system boundaries and functional units limits the capacity to make comparisons across CDR technologies.

The overall quality and comparability of LCA studies could be enhanced with guidelines around the most critical aspects of LCAs, including system boundaries, functional unit, temporal aspects, life cycle impact assessment categories (e.g., water use, land use, energy use, biodiversity, albedo change, competition with food production, etc.), and recommended data sources for inputs. Mechanisms should also be developed to guide decisions on when to adjust accounting protocols as scientific understanding changes. These mechanisms would ultimately provide greater clarity to the market on how and when factors may change.

In 2023, the LCA/TEA Technical Track will initiate a series of LCA case studies to advance globally shared methods, definitions, and boundaries.

The harmonization of life cycle assessments and techno-economic analyses will unlock greater insights into the environmental, social, and economic implications of CDR. These tools will have a significant impact in understanding the potential of these technologies and how, where, and at what rate CDR solutions are going to be deployed at a local, national, and international scale.

### Activity 1.1: LCA/TEA Case Studies

The LCA/TEA technical track will convene international experts to undertake a stepwise comparison of LCA/TEA methodologies (including boundaries, assumptions, etc.) on given case studies to identify potential differences, increase transparency, identify regional advantages/disadvantages, and aim for greater harmonization.

To interpret and compare LCAs in a meaningful way, complete life cycle inventories must be made available, and modeling assumptions disclosed. This presents a challenge for proprietary technologies such as DAC. As such, it may be necessary to develop process models to enable the cross-country comparison of LCA methodologies and advance globally shared best practices.

To address this need, LCA/TEA technical track members will contribute to the identification and/or development of case studies that enable complete disclosure of data sets and modeling assumptions. Case studies can build on existing and ongoing work, or planned future work by member countries and/or partners and should involve:

- Identification of CDR scenarios for analysis, in the three priority areas (DAC, BiCRS, EM), by different member countries, so a global perspective is developed. For example, a case study can be conducted for the application of direct air capture in different geographic areas and climate conditions that have a defined physical boundary as well as a system boundary with temporal considerations. Such studies can also include for example performance assessment of DAC sorbents' capacity, kinetics, and degradation rates. Moreover, the most beneficial way to utilize or store the $CO_2$ captured by direct air capture can be assessed by each country.

The key outcomes of LCA/TEA case studies include:

- Development of publicly available process models & tools with disclosed data and assumptions for DAC and BiCRS to enable international comparison.
- Comparative assessments of methodologies, including key definitions, assumptions, system boundaries, etc. for each selected case study.
- Share best practices and lessons learned (through Activity 2 below).
- Development of standards for assessing technology scenarios and cost reduction opportunities through techno-economic assessments for CDR technologies (DAC, BiCRS, EM).
- Potential development of a data-driven decision-making integrated model for CDR technology assessment, future scenario implementation, scaling up, and deployment in different jurisdictions including differences in regulations, infrastructure, and resource availability.

Timeline: LCA case studies will be launched in 2023. TEA case studies will be initiated in 2024.

### Activity 1.2: Development of Best Practices and Assessment Guidelines for LCA/TEA

As an assessment framework, LCA is governed by ISO standards 14040 and 14044. A separate standard, ISO/WD TS 14067, focuses on eco-techno economic analysis (eTEA), while ISO 14064 is also relevant for quantifying and reporting removed GHG. However, these standards are generic and do not offer guidance for specific technology applications. To foster consistency of LCAs to enable a more complete understanding of the potential impacts of CDR, the LCA/TEA technical track will develop a set of Best Practices and Assessment Guidelines for the conduct of LCAs and TEAs based on ISO standards 14040/14044, 14064, and 14067.

These guidelines should focus on the most important LCA/TEA aspects, including:

- Consistent systems boundaries, allocation methods, and functional units (to allow for the reliable comparison of CDR technologies, and the identification of CDR pathways with the best overall performance);
- Life Cycle Inventory Assessment categories (including both environmental and social impacts);
- Best practices for incorporating multi-functionality (e.g., by-products, co-benefits) and temporal aspects;
- Recommendations for background data sources;
- Recommendations for transparent data collection and data sharing;

- Minimum requirements for reporting the underlying assumptions, parameters; methodologies, and results of a TEA;
- Methodologies for estimating levelized cost of CDR technologies.

Considerations will also be needed in terms of:

- Determining the mechanism for adoption of guidelines and harmonization of methodologies at an international scale; and
- Engagement with private sector organizations to ensure alignment with existing efforts.

It is expected that the CDR LCA/TEA Best Practices and Assessment Guidelines will be shared with a wide array of audiences including technology developers, federal funding sponsors, national and sub-national level government policymakers and regulators, entrepreneurs, and investors interested in evaluating CDR technologies market, and potential host communities for CDR technologies. Engagement with these stakeholders will be critical to accelerating the development of CDR technologies by ensuring their future demand. As such the LCA/TEA track will leverage the MI CDR platform and carbon management organizations such as Frontier Fund for increased CDR technologies deployment and market penetration.

Timeline: Best Practices and Assessment Guidelines to be drafted in 2023, for publication in 2024.

### Additional Considerations for the LCA/TEA Technical Track Case Studies

It is also expected that LCA/TEA case studies under the LCA/TEA Technical Track will:

- Be time-bound and/or have clear project milestones.
- Be conducted by CDR Mission members and/or in partnership with external organizations.
- Clearly outline expected financial needs or contributions.
- Be developed in consultation with LCA/TEA Technical Track co-leads (Canada and/or Japan).
- Develop results and data that can be shared widely with CDR Mission members and the public to improve the availability of data and close data gaps in CDR LCA/TEA.
- Remain within the scope of the three technological priority areas (direct air capture, biomass with carbon removal and storage, and enhanced mineralization).
- Where possible, support training and development opportunities for highly qualified personnel (HQPs) and post-secondary students.
- Make clear relevance and linkages to the broader Carbon Dioxide Removal Mission under Mission Innovation (see Carbon Dioxide Removal Mission Action Plan).
- Work to make LCA/TEA datasets available to the public, in a generally accepted format by the end of the project (to facilitate Activity 3.2: Launch Data Hub).

## LCA/TEA Track Objective 2: Assess and Address Data Gaps

LCA is hindered by a lack of available data, especially for early-stage technologies. Harmonization of studies is only possible when sufficient technical performance data is also provided in addition to the LCA results.

Since many CDR pathways involve low TRLs, limited data are available to provide input for conducting the LCAs. As a result, there is high uncertainty with parameters required to assess many CDR processes, and these uncertainties can compound and lead to a large margin of errors. There are also challenges connected to gathering data due to the lack of guidelines.

Data generated through R&D across technical tracks can/should be shared with the LCA track to enable LCAs across a wider range of contexts and variables. For example, data on mineralization kinetics, biomass feedstocks, or sorbent capacity across a wide range of temperatures will all advance LCA objectives. There is also a lack of data around the social impacts of CDR technologies.

### Activity 2.1: Assessing Data Gaps

A preliminary assessment of data gaps was undertaken in the CDR Mission Innovation Roadmap.

- Develop a process for identifying and prioritizing critical data gaps (e.g., identify gaps that inhibit the real-world technical, economic, or life cycle performance of CDR technologies).
- Maintain an up-to-date registry of key data gaps by technology pathway.

Timeline: Ongoing.

### Activity 2.2: Addressing Data Gaps

The emerging and proprietary nature of CDR technologies presents challenges for the collection of data needed to enable detailed Life Cycle Inventories, and there is limited existing social impact data. There are also challenges related to gathering data due to a lack of guidelines.

Known data gaps include:

- CDR technology performance in different environments, and system conditions (e.g., understanding the efficacy of CDR technologies in cold climates.); and
- Environmental impacts, including potential trade-offs for non-climate change metrics, and co-benefits of CDR technologies.

To address this, LCA/TEA technical track members will commit to:

- Develop an LCA template to enable the consistent collection of data.
- Where possible, share data from all CDR-related R&D (e.g., data on mineralization kinetics, biomass feedstocks, or sorbent capacity across a wide range of temperatures will all advance LCA objectives.)

- Where possible, share data from all CDR demonstration projects, including those under the CDR Launchpad.

Timeline: Ongoing. LCA template to be developed in Spring 2023.

## LCA/TEA Objective 3: Identify and Launch Data Sharing Hub/Platform

The lack of data available for LCAs will be addressed through a public data-sharing hub. Through the development of open-source tools and models for LCA/TEA for CDR technologies and the creation of public data sets, the LCA/TEA track will advance global capacity to undertake rigorous LCAs.

### Activity 3.1: Identify and Agree Upon a Data Sharing Hub

Discussions have been ongoing between Natural Resources Canada (NRCan) and the National Research Council (NRC) to contribute the results from various member countries involved in the LCA/TEA Technical Track to NRC's cloud-based hub OpenLCA to store, validate, and make available life cycle analyses data which could lead to more accurate assessments of carbon dioxide removal technologies.

The NRC is currently developing two cloud servers to address the requirements of a Data Hub:

- NRC OpenLCA collaboration server with a data warehouse:
    - This will enable researchers/users within and outside the NRC to collaborate in the development of LCA/TEA data sets.
    - This platform is being used for the $H_2$ pathways assessment (funded by NRCan and Environment and Climate Change Canada (ECCC)) with technical contributions from universities, NRCan's CanmetEnergy teams, ECCC, and others.
- LCA/TEA Webserver for CCUS pathways

The proposed data hub is funded by NRC Materials for Clean Fuels program.

Timeline: Technical track members will agree upon the data hub by Spring 2023.

### Activity 3.2: Launching Data Hub/Platform Activity

Through this activity, the LCA/TEA Technical Track will work to streamline data collection, entry, and validation in a publicly available collaboration server.

Implementation of the data-sharing platform will take a staged approach to build a case for an open science data platform.

Stage One: Identify one (maximum two) CDR pathway(s) for which harmonized/transparent datasets will be developed and integrated into the OpenLCA collaboration server.

- Develop a Life Cycle Inventory (LCI) template for consistent collection of data;
- Collect and amalgamate LCA/TEA data from different sources (primary & secondary); and

- Complete quality control, data formatting & conversion, and impact assessment.

Stage Two: Demonstrate the feasibility and importance of open data to help effective/timely decision-making for climate change crises. From there, we can build a strategy and identify direct funding to roll out this approach to all other CDR pathways.

Timeline: The data hub will be launched by the end of 2023.

## LCA/TEA Objective 4: Assess CDR Scale-Up

The deployment of CDR technologies at scale is still theoretical, with only limited demonstration projects currently online. Consequently, most CDR technologies are not sufficiently examined regarding their overall environmental performance.

The need for transformative, large-scale deployment of CDR suggests that the traditional small-scale functional unit approach to LCA/TEA will not adequately capture the resulting environmental and economic impacts of CDR technologies. The boundaries of the LCA/TEA must therefore consider both the climate and other environmental impacts of CDR deployed at scale.

### Activity 4.1: Assessing CDR Scale-Up

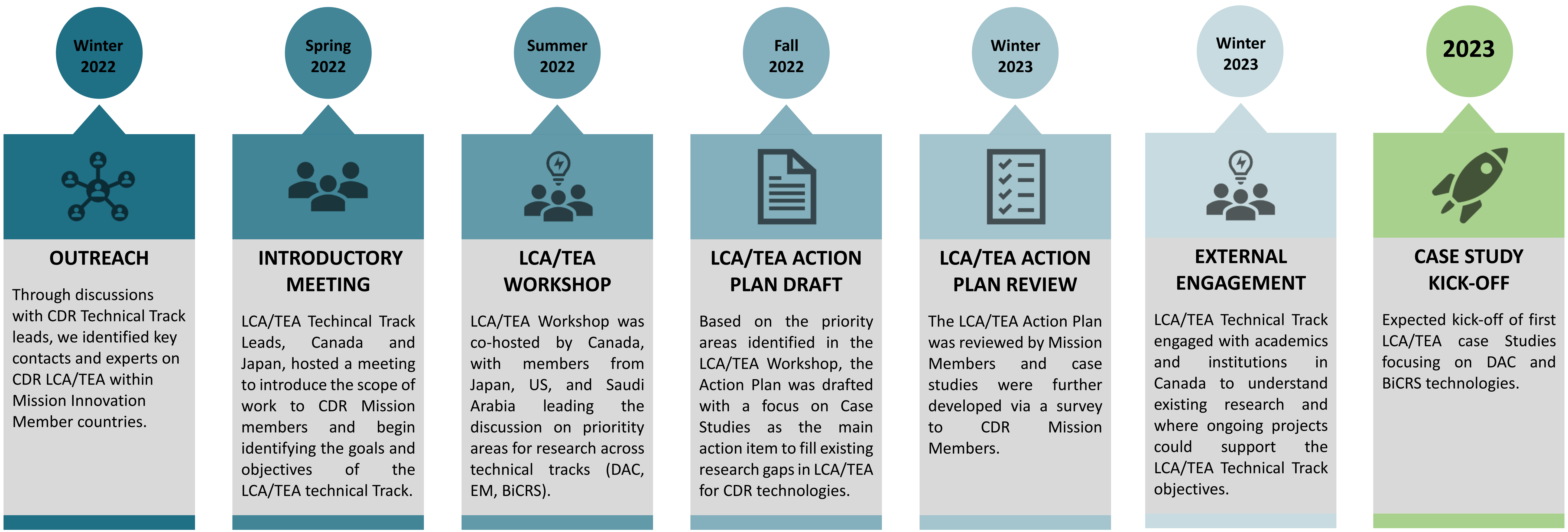
- Assessing the impacts of CDR deployment at scale requires an expansion of LCA/TEA boundaries to include a more detailed representation of background systems and interactions via energy system modeling, comparison of CDR with competing mitigation technologies, and improved characterization of climate impacts by integrating CLA/TEA results with the parameters used by climate modelers.
  - Advanced methods to comprehensively assess environmental impacts and economic potential of CDR (e.g., incorporation of CDR in climate and energy system models)
- Examine impacts of CDR deployment at scale, including how CDR technologies will interact with climate through albedo, water use, land use, and particulate matter (in addition to GHGs)
- Evaluation of CDR technologies (DAC, BiCRS, EM) on the whole energy system level.
- Analysis of future scenarios and opportunities for improvement/global collaboration for CDR technologies (DAC, BiCRS, EM)
- Assessment of non-technical factors such as policy, regulatory and socio-economic factors in the potential for the wide-scale deployment of CDR technologies (DAC, BiCRS, EM).
- Assessments of future scenarios. For example, an assessment of biomass supply chain for BiCRS (biomass with carbon removal and storage) or an assessment of energy options for driving DAC process.

- This work will be led by Canadian academic experts, in collaboration with LCA technical track members. Work undertaken domestically will be shared through various knowledge-sharing events and fora.

Timeline: 2023 – 2028.

## Implementation Plan and Timelines

To develop the objectives and case studies under the LCA/TEA Technical Track, a workshop was held in July 2022 to define project scope and opportunities for case studies. When the case studies launch, they will start with the identification of available data, as well as the available resources to guide and inform the studies. Functional Working Groups (WG) will be formed for each case study and will be responsible for managing the planning and execution. These WGs will work collaboratively to define the specific LCA/TEA projects to be studied and identify the participants. The graphic below describes the actions taken to date and expected future activities for the LCA/TEA Technical track.



## Expected Activities for 2023 and Later

### Publication of Action Plan

By May 2023, it is our objective to have this Action Plan finalized and agreed upon by all Mission members, including agreement from representatives of Canada, Japan, the US, Norway, Saudi Arabia, Australia, and the UK. Once finalized, the Action Plan will be published along with the Action Plans developed by other technical tracks.

### Case Studies Development

As of May 2023, the scope, and objectives of all case studies (Annex 1-5) are still in draft form. Therefore, the LCA/TEA Technical track must work with partner countries to further develop the scope of work, goals, timelines, and expectations of those case studies. In addition to the Annexes below, internal, and formalized documents should be created for the case studies, which will outline project milestones, funding commitments, and deliverables to the greater CDR Mission for the duration of the project.

Beyond what has been mentioned above, additional engagement is needed to scope and develop an LCA/TEA case study for enhanced mineralization. It has been highlighted that as enhanced mineralization is a relatively new area of CDR research, LCA/TEA case studies may work toward mapping and evaluating enhanced mineralization feedstocks and their viability for carbon dioxide removal.

### Workshops and Events

The LCA/TEA Technical Track should aim to deliver quarterly to bi-annual workshops or webinars to the wider group of MI CDR participants. Topics for workshops or events may include:

- Dissemination of case study findings.
- Discussion of new/changing policies related to CDR LCA/TEA from member countries.
- Research talks from academic/scientific experts from LCA/TEA Technical Track working groups.
- Forward-looking brainstorming sessions on the future of the LCA/TEA Technical Track.

### Continued Engagement

Beyond the objectives noted above, the LCA/TEA Technical Track will continue to engage with member countries and stakeholders to advance shared priorities related to enhancing LCA/TEA for carbon dioxide removal technologies. The LCA/TEA technical track will lead activities that engage science and policy experts and program administrators to harmonize CDR LCA/TEA across direct air capture, biomass with carbon removal and storage, and enhanced mineralization. Engagement and knowledge sharing within broader international governmental initiatives like MI CDR are key to creating fit-for-purpose LCA/TEA frameworks.

# Annexes

To develop this project, an LCA/TEA Workshop was held in July 2022 to scope priority areas and opportunities for case studies. Functional Working Groups (WGs) will be formed for each case study and will be responsible for managing the planning and execution. These WGs will work collaboratively to define the specific LCA/TEA projects to be studied and identify the participants in each project. The case studies will support the main objectives of the LCA/TEA Action Plan, harmonize LCA/TEA studies for CDR, and work to create a global data hub for LCA and/or TEA.

## LCA/TEA Case Studies/Projects

## Annex 1 - Direct Air Capture

### Timeline

- January 2023 – December 2023

### Scope and Objectives

- Define suitable physical/system boundaries for assessing DAC.
- Develop specific methods and standards, including a distinction between "avoided emission" and "negative emission".
- Case study for the application of direct air capture in different geographic areas and climate conditions.
- Data collection of DACs including process flow, energy consumption, material consumption, and operating conditions.
- LCA/TEA case study of DAC+CCUS within different countries. Analysis of future scenarios for international collaboration.

### Implementation Plan

- Timelines:
  - Meetings will be held approximately once a month to share collected data and case study results.
  - Accounting methods, system boundaries, and case study results developed through these meetings will be presented and shared.
  - LCA/TEA case study of DAC will be completed in 2023.
- Initiate a DAC case study using an LCA/TEA tool developed by Canada, Japan, and USA and in parallel, analyze:
  - Data to be collected (*e.g.*, process flow, energy consumption in different geographic areas and climate conditions, scale, merit, supply chain, and land area required to build DAC facilities).
  - Methods and standards to be established (*e.g.*, accounting method, system boundary, and temporal aspect).

    - Application of DAC in different sectors, including an analysis of advantages and disadvantages of implementing DAC in each country using LCA/TEA results
    - Document data on the climatic and non-climatic impacts such as biodiversity loss pollution etc. and mitigation measures deployed.
- Utilizing the LCA/TEA tool developed by Japan, USA, and Canada, initiate a case study of DAC+CCUS (carbon capture utilization and storage) and:
    - Complete LCA/TEA case study of DAC+CCUS within different countries and utilization scenarios (methanol, aviation fuel, shipping fuel, high-value products, and storage).
    - Identify the most beneficial supply chain considering the advantages and disadvantages of each country.
    - Provide an analysis of future scenarios for international collaboration.

### Data to be Collected

The following simulation and analysis data from different DAC processes will be collected:

- Process flow, energy consumption, material consumption, $CO_2$ emissions, heat balance, cost (CAPEX and OPEX), scale, merit, land area, and operating conditions.
- Process flow diagrams.
- Sensitivity analysis data considering different operating conditions (by process simulation).
- Uncertainty analysis.
- Literature-based data for comparative analysis with data collected through simulations.
- Challenges of DAC implementation in different countries, including policy, social, and economic barriers.

## Annex 2 -BiCRS

### Timeline

- January 2023 – December 2023

### Scope

Performing LCA for at least two cases/technologies. For example, within CCS-WtE incineration of non-hazardous municipal waste containing biomass or CCUS-biomass conversion to fuel and carbon products, each with at least two different approaches and/or at least two different countries:

The work shall include:

- Definition of physical/system boundaries.
- Use of transparent and documented data inventories, including process flow, energy consumption, material consumption, and operating conditions.
- Use of transparent methods and documented LCA.

- The LCAs must document how they address climate impacts of direct and indirect land use, land use change and forestry, competition with other uses of land, water consumption, and impacts on biodiversity, carbon, and hydrological cycles, as well as trade-offs with the UN Sustainability Goals. The LCAs must also address non-climate impacts, such as ecotoxicity and eutrophication.
- Discussion on how the choice of the baseline can impact the calculation of negative emissions.

Norway is leading the BiCRs LCA/TEA track with support from member countries such as Canada that will be developing case studies in biomass gasification with carbon capture and storage and potential pilot and demonstration projects. This BiCRS LCA/TEA case studies section will be updated with detailed workplans of other supporting member countries in the future.

### Objectives

- Improve understanding of differences and shortcomings in LCA for BiCRS.
- Develop specific methods and standards, including the distinction between “avoided emission” and “negative emission”.
- Increase understanding of suitable biomass feedstock & conversion technologies and definition of “permanence of storage” in carbon products.

### Implementation Plan

- Initiate at least two BiCRS case studies in at least two member countries with different geographic and climate conditions and different biomass feedstocks e.g., waste streams, energy crops, and residues. Using LCA methodology developed in these countries.
- Identify and document methods and data.
- Evaluate the results in form of differences in results and methods and convey to the LCA/TEA technical track for improvement.
- Hold meetings at regular intervals to share collected data and case study results.
- Accounting methods, system boundaries, and case study results developed through these meetings will be presented and shared.

### Outcome

- Recommendations to the LCA/TEA Technical Track on how LCA for BiCRS can be improved.

## Annex 3 – Canadian Expert Working Group

### Project 1: Integrated Assessment of Carbon Dioxide Removal Technologies-University of Alberta

#### Timeline

- April 2023 – March 2028

## Scope and Objectives

The scope of the proposed work will be achieved through the following sub-projects:

- Develop a framework for the assessment of BiCRS and evaluate the potential for BiCRS in Canada including:
    - Determining BiCRS potential feedstocks and the amount available in Canada.
    - Examine carbon sequestration potential via BiCRS considering the life cycle concept.
    - Conduct an integrated Assessment of BiCRS incorporating the LCA in an energy system to evaluate the full impact on the energy system.
    - Identification and assessment of joint BiCRS projects between the member countries (e.g., transport of $CO_2$ from one country to another).

- Carry out an integrated assessment of the impact of the implementation of DAC in the Canadian Energy System using the Low Emissions Analysis Platform for Canada (LEAP-Canada) in collaboration with MI partner countries working on the LCA and TEA of DAC including:
    - Identifying DAC (Direct Air Capture) technologies that are suitable for Canada's colder climate.
    - Evaluating the Cost and Life Cycle Greenhouse Gas Footprint of DAC Technologies in Canada.
    - Development of potential penetration profile of DAC in Canada.
    - Integrated assessment of DAC incorporating the LCA/TEA in the Canadian energy system for evaluation of the full impact on the energy system for policy formulation and investment decision-making.

- Develop a framework for assessment of EM technologies in terms of their costs and life cycle GHG footprints including:
    - Determine the potential of EM-based carbon removal technologies.
    - Examine the potential of carbon sequestration through EM considering the life cycle concept.
    - Integrated Assessment of EM incorporating the LCA in an energy system for evaluation of the full impact on the energy system which can help in policy formulation and investment decision-making.
- International Collaboration
    - Collaborate with international partners via email, video conferencing, and at in-person workshops.

## Implementation Plan

- Identify and document BiCRS (biomass) and EM (rocks) feedstocks from existing data sources in government, industry, academia in different Canadian jurisdictions, etc.
- Identify obstacles to accessing and using data across jurisdictions and develop a framework for estimating feedstocks, GIS mapping tool, and DAC penetration model.
- Recruit and train HQPs in the three main technical areas of CDR – DAC, BiCRS, and EM, along with climate and energy impact modeling

- Share accounting methods, system boundaries, and case study results of different LCA/TEA scenarios through meetings, conferences, and peer-reviewed publications.
- Evaluate the results in the form of differences in results and methods and convey to the LCA/TEA technical track for improvement and sharing on a data exchange and learning platform.
- Hold meetings at regular intervals with NRCan technical advisory committee to keep track of project objectives and MI partners to share generated data, learning outcomes, and case study results.

## Project 2: Advancing Data and Methods for CDR Assessment-University of Calgary

### Timeline

- April 2023 – March 2026

### Scope and Objectives

The objectives of the proposed project will be achieved through the following sub-projects:

- Measurement of DAC sorbent properties to establish a benchmark for LCA and TEA including:
    - Conduct experimental tests of commercially available sorbents that could be used in DAC under environmentally relevant conditions at the granular scale to fill data gaps for LCA and TEA.
    - Collaborate to establish an open performance benchmark for pressure-vacuum swing DAC systems based on acquired experimental data.
    - Develop new or modify existing process models that will be used to optimize cycle performance under different climate conditions.
    - Use results for DAC system performance in the ongoing life cycle and techno-economic assessments.

- Extending LCA and TEA of BiCRS systems to a wide range of feedstocks including:
    - Examine a range of BiCRS feedstocks, conversion technologies, and products, as well as expanded scale-up and deployment scenarios.
    - Develop a database for energy crop feedstocks and residues (other than conventional forestry and agricultural)—including crops that can be grown on marginal land, supply chain requirements, and implications of climate change.
    - Explore scale-up and deployment aspects of BiCRS technologies, including an assessment of the permanence of $CO_2$ removals.
    - Identify the potential of technological advances, including new BiCRS pathways, to improve life cycle environmental and economic performance relative to current systems.

- Closing the loop between CDR assessment, climate, and energy systems including:
    - The interactions between the energy system and CDR technologies.

    - Trade-offs between potentially costly mitigation of "residual" emissions (e.g., use of biofuels or synthetic $CO_2$-based fuels in long-haul aviation) versus continuance of some de minimis level of emissions combined with CDR.
    - The climate impacts of CDR deployment scenarios through the development of simplified, open-source climate emulators.
    - Simplified climate emulators to rapidly assess CDR deployment scenarios.

- Accelerating and integrating laboratory measurements of reactivity for LCA and TEA of EM including:
    - Temporal aspects of EM location in conjunction with laboratory-measured reactivity to enhance the data being fed into the LCA and TEA models.
    - Additional uncertainty analysis, expanding the parameters of the LCA and TEA integrated models.
    - Consideration of non-climate impacts in the LCA of EM, such as the land footprint required, capital and operational expenses for changes to ore processing and tailings management, water required in more arid areas for optimum mineral reactivity with $CO_2$, etc.

- International Collaboration
    - Collaborate with international partners via email, video conferencing, and at in-person workshops.

### Implementation Plan

- Define specifications and purchase measuring equipment for DAC and EM experimentation.
- Engage a consultant to collect and aggregate data on biomass supply in Canada into a publicly available and accessible data set.
- Recruit and train HQPs in the three main technical areas of CDR – DAC, BiCRS, and EM, along with climate and energy impact modeling.
- Share accounting methods, system boundaries, and case study results of different LCA/TEA scenarios through meetings, conferences, and peer-reviewed publications.
- Evaluate the results in the form of differences in results and methods and convey to the LCA/TEA technical track for improvement and sharing on a data exchange and learning platform.
- Hold meetings at regular intervals with NRCan technical advisory committee to keep track of project objectives and MI partners to share generated data, learning outcomes, and case study results.

## Annex 4 –Literature Review of LCA/TEA Methodologies

### Timeline

- January 2023 – December 2023

### Scope and Objectives

Japan will compile a literature review of LCA methodologies and LCA/TEA inventory data of CDR technologies (DAC, BiCRS, EM). Japan would work with an external contractor to develop a report, which could be shared with all CDR Mission members (not only the LCA technical track).

## Annex 5–Enhanced Mineralization

### Timeline

- April 2023 – March 2027

### Scope

Developing and deploying CDR requires systems thinking, multi-disciplinary approaches, and co-dependent decisions across value chains. Decision support tools are needed that integrate the best available scientific knowledge to inform a range of policy and/or market decisions. They should evaluate and analyze cutting-edge scientific data using computational methods, modeling techniques, and/or data integration, to inform policy needs. The analysis will include consideration of negative emission technologies such as enhanced mineralization to allow nations to meet their net-zero emissions target.

While the Kingdom of Saudi Arabia and Australia will be co-leading the EM case studies of the LCA/TEA track, other member countries such as Canada through the Canadian Expert Working Group-CanmetENERGY Ottawa whose workplan is presented here will be supporting the EM track. Note that this section will be updated subsequently with case studies from the co-leads and other countries.

### Objectives

- Create a decision support platform for strategic planning of CDR, considering industry type and future intentions/goals, existing and novel removal pathways, long-term storage potential, and temporal adoption of CDR.
- Determine the lowest cost and the lowest environmental impact pathways for enhanced mineralization.
- Provide the necessary data and models to evaluate the competitive position of enhanced mineralization at the regional, sectoral, and national levels.

### Implementation Plan

- Determine suitable materials/process by-products for enhanced mineralization.
    - Identify current and future sources, along with capacities (e.g., $tCO_2$/year removal capacity)
- Work with project partners/universities to determine reaction pathways and thermophysical properties of $CO_2$ removal materials.
- Develop process flow diagrams, identifying major streams and equipment.
- Process simulation, optimization, and template development for candidate technologies.
    - Heat, material, and power balances.

    - Case studies to generate performance, equipment sizing, and input/output stream data.
- Determine technology costs (CAPEX and OPEX) and generate cost functions using machine learning tools.
- Determine environmental impacts of enhanced mineralization via LCA using machine learning tools.
    - Comparison of enhanced mineralization versus $CO_2$ sequestration versus utilization.
- Integrate materials amenable to enhanced mineralization as an additional map layer in ArcGIS.

### Outcome

Key project results/recommendations will be conveyed to member countries through a mix of scientific journal publications, and technical presentations.